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Breathing under high ambient pressure[1]

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LORD, GEORGE P., GEORGE F. BOND, AND KARL E. SCHAEFER. *Breathing under high ambient pressure.* J. Appl. Physiol. 21(6): 1833–1838. 1966.—The acute effect of high ambient pressure on expiratory airflow was studied in healthy adult males in the ambient pressure range from 1.0 to 7.0 atmospheres absolute pressure (Ata) using a hyperbaric chamber. Changes in flow were assessed with the maximum expiratory flow-volume curve. The decrease in flow was compared to that occurring in dense high molecular weight gas mixtures. In addition, expiratory gas flow was studied in three men during 12 days at 7.0 Ata in 90% helium. The findings demonstrate that: *1*) high ambient pressure and high molecular weight gas of equal density produce similar changes in expiratory flow; *2*) in the pressure range from 1.0 to 4.0 Ata in air the greatest decrease in maximum expiratory flow occurs at high lung volumes, while from 4.0 to 7.0 Ata the greatest flow change occurs at low lung volumes; *3*) the long-term changes in expiratory flow in high-pressure helium can be explained by the change in physical properties of the breathing mixture; and *4*) there are no clinically apparent untoward effects from prolonged high-pressure helium breathing.

pulmonary function; helium breathing; maximum expiratory flow-volume curve; hyperbaric physiology; acclimatization to high pressure

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THE DECREASE observed in expiratory gas flow in a high ambient pressure environment is assumed to be the result of increased ambient gas density (1, 2, 4, 9, 13–16, 20, 21). This concept underlies our understanding of gas flow under high pressure in the human airways and it forms the basis for selection of atmosphere composition to be used during prolonged underwater exposure (8). To test this fundamental premise, expiratory gas flow under high pressure in air was compared to that of high molecular weight gases at sea-level pressure as studied by Schilder, Roberts, and Fry (19).

High molecular weight and high ambient pressure both increase the density of the respiratory medium. If the same decrease in flow occurred with an equivalent change in density using each method, it is reasonable to conclude that, so far as gas flow in the human airway is concerned, an increase in the number of moving particles (with high ambient pressure) has the same effect as an increase in their molecular weights. This proved to be so.

A second portion of this study was designed to determine the effects of prolonged exposure to helium in 90% concentration at 7.0 atmospheres absolute pressure (Ata).

METHODS

Relationship of density and pressure. The maximum expiratory flow-volume curve (MEFV) was used as a basis for comparison (6, 7, 11). This technique measures expiratory flow rate at each instant during a forced expiration. Expiratory flow versus lung volume is depicted as ordinate and abscissa, respectively, of a simple *x-y* plot. The "flow-volume" curve evolved is essentially a high resolution spirogram in which small changes in flow during expiration are easily discerned.

The maximum expiratory flow-volume curve was introduced by Hyatt and Fry in 1960 (6, 7, 11). In the present study the MEFV was recorded with the subjects standing, connected by wide-bore, smooth-walled tubing to an electronic wedge spirometer (model 370, Med-Science Electronics, St. Louis, Mo.). The curves were photographed outside the pressure chamber from the face of a cathode-ray oscilloscope (Tektronix, type 520A, Portland, Ore.). The frequency response of the wedge spirometer to a rapidly changing flow input was checked at ambient pressure by the manufacturer and found to be within 5% at 22 cycles/sec. The frequency response was not determined under pressure.

Flow-volume curves were recorded at a series of pressure stops during decompression from 7.0 to 1.0 Ata using standard US Navy decompression tables. The flow and volume response of the wedge was determined at each stop by connecting the wedge to a standard Collins bell-type spirometer. Lead weights were placed on the bell of the Collins and it was allowed to descend, forcing air into the wedge. As the bell descended, an electrical contact was made at each of two points separated by exactly 2 liters of volume marked on the side of the Collins. These electrical contacts were visualized as two

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pips on a rapidly moving precalibrated direct-writing recorder. Flow rate between the contacts was observed to be steady by checking the voltage output of the wedge spirometer. By determining the time required for the Collins to express 2 liters, a mean flow rate was determined. Each flow rate produced by the falling bell and expanding wedge was visualized on the oscilloscope and photographed. Later, a regression line was drawn through the points plotting measured flow rate from the Collins against millimeters of deflection on the oscilloscope face as a direct measure of flow rate from the wedge. The departure of this regression line from the internal flow calibration signal of the wedge amplifier was then determined. The difference between the measured flow and the electrical calibration was never greater than 3.2 % at any pressure. It was usually less than 1.0 %. When in error, an appropriate correction was applied during calculation of the data.

After familiarization with the procedure, the subject's nose was clamped and he was asked to inhale to peak lung inflation. No attempt was made to establish a particular pattern of inspiratory airflow. At a signal, he exhaled maximally and the flow-volume curve was recorded. Exhalations were repeated until the flow-volume curve evolved subtended a maximum area with the volume abscissa. All curves were photographed and the one with maximum area was later determined by planimetry. This curve, by definition, is the maximum expiratory flow-volume curve. After obtaining three such MEFV curves at sea level, the chamber was pressurized to 7.0 Ata with air. MEFV curves were then recorded in triplicate during decompression from 7.0 Ata to sea level, with stops at 6.0, 5.0, 4.0, 3.0, 2.0, 1.7, and 1.3 Ata. Four subjects were studied—two of them twice.

Twelve-day exposure to 7.0 Ata in helium-oxygen-nitrogen. Two experienced US Navy divers were accompanied by a physician into a 30 m[3] pressure chamber for the 12 day compression at 7.0 Ata. All were fully aware of the hazardous nature of the study. All food and supply packages had been perforated to prevent crushing under pressure. A diving officer and a physician were in constant attendance outside the chamber. A stand-by pressure system was available in the event of accidental explosive decompression. Physiological data of the subjects appear in Table 1.

TABLE 1. *Physiological data*

Subj	Age, yr	Ht, cm	BSA, m^2	VC, liters (BTPS, %)	RV/TLC*	1 sec TVC, %	MBC, liters/min (BTPS, %)
JB	28	170	1.83	a 5.03 (102)	17	88	194 (150)
				b 5.05		70	137 (106)
RB	32	181	2.05	a 6.34 (120)	20	86	186 (115)
				b 6.55		77	132 (82)
SM	32	164	1.73	a 4.62 (103)	28	82	128 (106)
				b 4.41		64	113 (93)

a = control state, air at 1 Ata, b = after 10 days at 7 Ata; predicted normal values (17). * Residual volume calculated by the method of Rahn, Fenn, and Otis (18).

TABLE 2. *Composition of the atmosphere during the 12-day exposure at 7.0 Ata*

Gas	Partial Pressure, mm Hg
He	4658.0
O_2	204.0
N_2	299.0
CO_2	8.8
H_2O	26.0

1.7 g/liter (1.5 × air at 1 Ata)
204 μpoise (1.13 × air at 1 Ata)

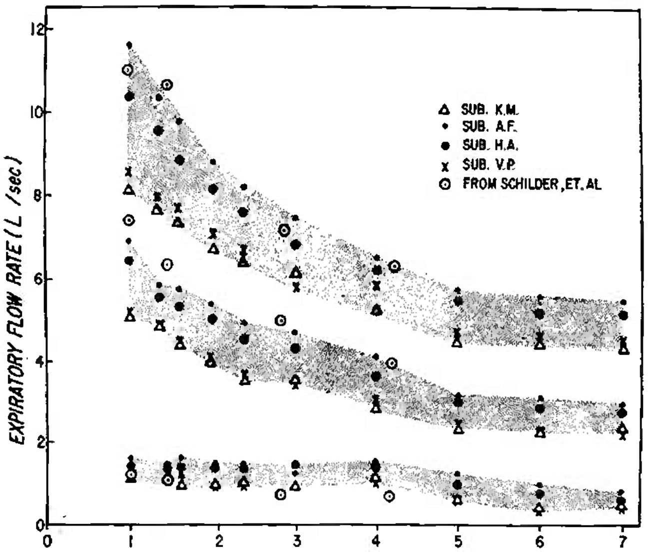

FIG. 1. The three shaded areas depict the changes in peak expiratory flow rate (upper area), flow rate at 50% of the vital capacity (middle area), and flow rate at 15% of the vital capacity (lower area) during compression of four subjects from 1.0 to 7.0 Ata in air. Each point represents data derived from three MEFV tracings recorded from each subject at each pressure. Changes in flow caused by high molecular weight gas (open circles) are similar to those caused by high pressure.

After the men entered the chamber the door was closed and helium was introduced into the chamber from banks of high-pressure cylinders outside, compressing the room air already present. Compression to 7.0 Ata required 1 hr and 45 min and was maintained for 12 days. At 7.0 Ata, the resulting atmosphere contained 89.6 % helium and 3.9 % oxygen (P_{O_2} = 204 mm Hg). Carbon dioxide concentration was maintained at mean of 0.17 % (P_{CO_2} = 8.8 mm Hg) by a lithium hydroxide absorption system. Partial pressures of the other gases appear in Table 2.

The calculated density of the mixture was 1.7 g/liter (approximately 1.5 times that of air), and the viscosity was 204 μpoises (1.13 times that of air)[3] (5, 10, 12). A gas chromatograph (Perkins-Elmer Fractometer, model 154 D, Norwalk, Conn.) continuously monitored partial pressures. Frequent checks of oxygen and carbon dioxide concentration were made with a Scholander microgas

[3] Calculation by B. S. Ryskiewich, Applied Mechanics Section, General Dynamics Corp., Groton, Conn. A copy of the viscosity calculation has been deposited as Document number 9061 with the ADI Auxiliary Publications Project, Photoduplication

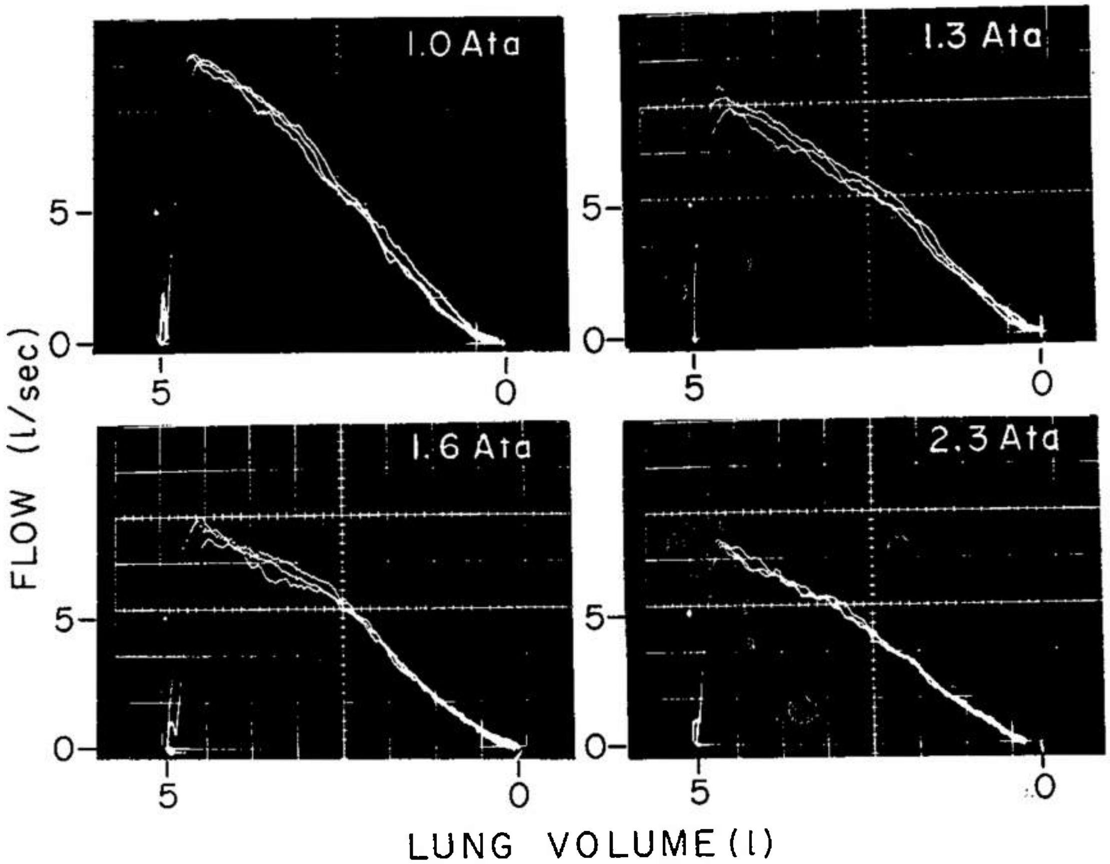

FIG. 2. Original MEFV curves from *subject HA* in air at 1.0 Ata, upper left; at 1.3 Ata, upper right; at 1.6 Ata, lower left; and at 2.3 Ata, lower right. The ordinate is expiratory airflow from the mouth in liters per second; the abscissa, lung volume in liters. The subject first inhaled to peak lung inflation (point 5 on the volume abscissa at each pressure), then he exhaled. Flow rate was measured throughout the course of expiration along the curve to the forced expiratory position, marked 0. Exhalation was performed in such a way that maximum flow was achieved at each lung volume. In this pressure range the greatest decrease in flow with rising ambient pressure is in the first half of expiration.

analysis apparatus. Trace gases were detected by mass spectrography.

Since it was not technically practicable to use the wedge spirometer for obtaining the MEFV curve under these conditions, the Collins spirometer was used after fitting it with a rapidly turning kymograph. This spirometer was calibrated in a manner similar to that used for the wedge spirometer in the acute experiments. With the kymograph turning at 30 cm/sec the subject inhaled from the end-tidal position to peak lung inflation and, at a signal, exhaled. At the end of exhalation, he was disconnected from the mouthpiece. Spirograms were repeated several times until they were reproducible. Each tracing measured over 1 m in length. It was divided into 0.04-sec intervals for calculation of flow rate. This calculation was performed independently by three investigators. Rotational velocity of the kymograph was determined with a stop watch.

The response of a Collins spirometer to a sudden increase in flow rate at the onset of a forced expiration is not as brisk as that of a wedge spirometer because the moving mass of Collins spirometer is greater than that of the wedge, and the water level under the Collins bell falls as it moves during the course of a rapid expiration. This damps the peak flow rate. Moreover, increasing the speed of rotation of the Collins kymograph increases the accuracy of instantaneous flow measurements only by increasing the time base. The momentary volume changes are not altered.

Taking these limitations into account, as the frequency response characteristic of the Collins spirometer was less than that of the wedge, the tendency would be for measurements of peak expiratory gas flow to be less than those on the wedge. Instead, measured flow rates were generally greater than those obtained during acute exposure in air before compression. While the precise assessment of flow rates at specific lung volumes was limited by the instrumentation, it seems likely that the directional changes are correct.

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RESULTS

Relationship of density and pressure. In Fig. 1 are presented the MEFV data derived from four subjects during acute exposure to air under high pressure. The upper

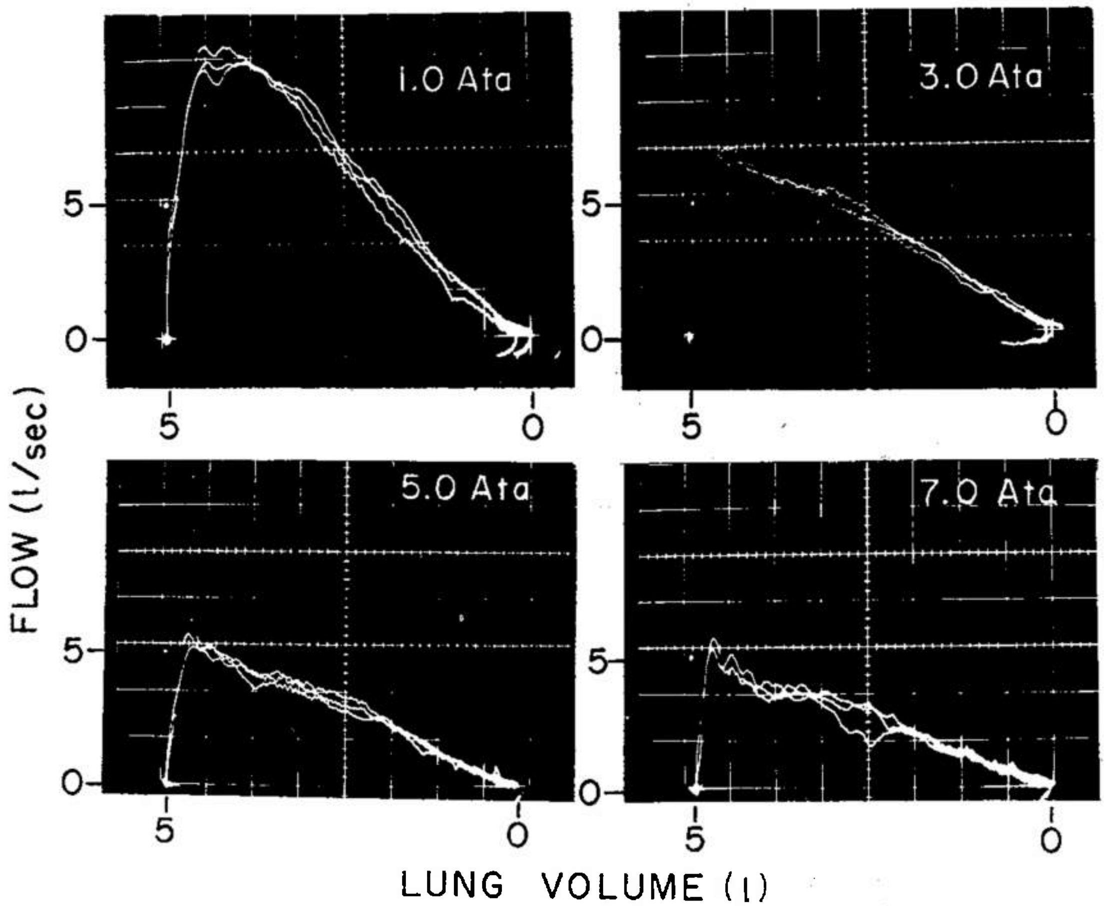

FIG. 3. Original MEFV records from *subject HA* taken in air at 1.0 Ata, upper left; at 3.0 Ata, upper right; at 5.0 Ata, lower left; and at 7.0 Ata, lower right. Coordinates are the same as in Fig. 2. Peak flow decreases little from 5.0 and 7.0 Ata, while mid and low lung volume flow continues to fall.

shaded area depicts the change in peak flow, the middle shaded area the change in flow at 50% of the vital capacity, and the lower shaded area the change in flow at 15% of the vital capacity, i.e., 15% above the forced expiratory position. The open circles are the data from Schilder, Roberts, and Fry (19) in high molecular weight gas. For comparison, the density of a given high molecular weight mixture is expressed as a multiple of the density of air at sea level.

Peak expiratory flow rate decreases sharply as pressure rises from 1.0 to 4.0 Ata (upper shaded area). Above 5.0 Ata little further decrease in peak flow occurs. Mid lung volume flow rate also falls rapidly in the first 4 atm of pressurization (middle shaded area). By contrast, low lung volume flow is little affected by the pressure rise from 1.0 to 4.0 Ata, but from 4.0 to 7.0 Ata it decreases progressively (lower shaded area).

These results clearly indicate that as ambient pressure rises maximum flow rates at high lung volumes behave in a manner opposite to maximum flow rates at low lung volumes. The maximum breathing capacity is usually performed slightly above mid lung volume, using near maximum flow rates (7). It is not surprising, therefore, that the changes in MBC with increasing ambient pressure parallel the changes in peak flow found here (16).

Original data obtained from *subject HA*, typical for the group, are depicted in Fig. 2 from 1.0 to 2.3 Ata and in Fig. 3 during another compression several days later from 1.0 to 7.0 Ata. The reproducibility of the curves at each pressure is evident. At sea level, expiration is characterized by a rapid rise to peak flow, followed by an expiratory descent which is nearly linear. From 1.0 to 2.3 Ata (Fig. 2), peak flow falls and the slope of the expiratory descent is decreased. Vital capacity is unchanged. In this pressure range, flow at low lung volumes remains smooth and regular.

The linear nature of the expiratory descent is altered by the increase in pressure from 1.0 to 1.6 Ata. At 50% of the vital capacity the curve shows a clear inflection point at 1.6 Ata. This suggests that high and mid lung volume flow is decreasing more rapidly than low lung volume flow under the impact of the density change.

Several days later, *subject HA* was restudied (Fig. 3). The MEFV tracings at 1.0 Ata are identical to those obtained earlier. Again, as ambient pressure rises, peak flow falls. The slope of the expiratory descent at 5.0 and 7.0 Ata is linear as it was at 1.0 Ata. There is little change in the total configuration of the curve between 5.0 and 7.0 Ata.

Prolonged exposure to 7.0 Ata in helium-oxygen-nitrogen. Flow rates after 10 days at 7.0 Ata in He-O_2-N_2 (Fig. 4, solid points) were within the range observed in the

subjects exposed to acute compression in air. In this figure the density of the helium mixture is expressed as an equivalent density of air at 1.7 Ata. The very high value of peak flow observed in air after decompression in *subject JB* (open circle at 13.5 liters/sec) is perhaps a reflection of this man's motivation. He was the physician who accompanied the other two divers during the

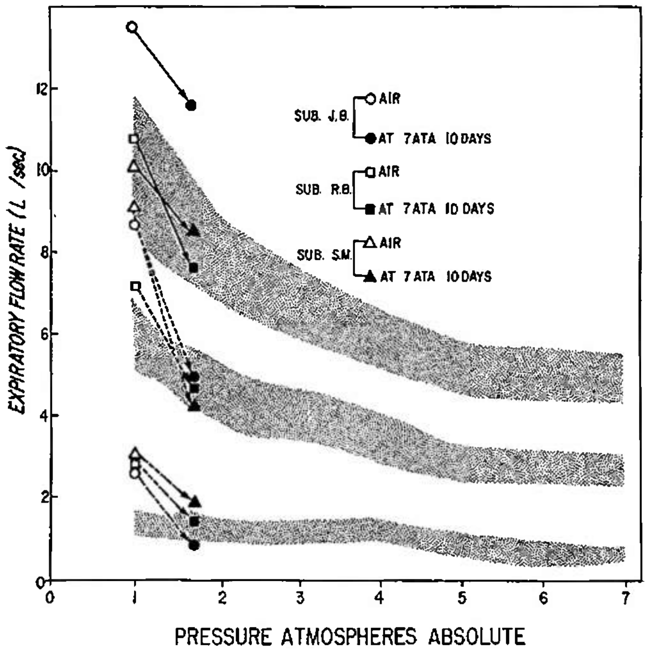

FIG. 4. The shaded areas are redrawn from Fig. 1 (acute exposure to air at high ambient pressure). The upper shaded area depicts peak flow rate; the middle shaded area, flow rate at 50% of the vital capacity; and flow rate at 15% of the vital capacity in the lower shaded area. Superimposed are the MEFV data from three subjects after 10 days of compression in 90% helium, 5% nitrogen, and 3.6% oxygen (solid points), and after decompression and return to room air (open points). Each point represents an average of three MEFV curves from each subject. When equivalent densities are compared, the decrease in flow rate during prolonged exposure to high pressure in helium is the same as during acute exposure in air.

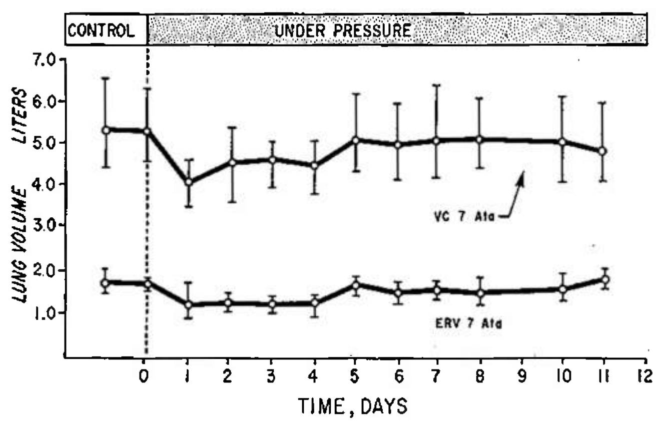

FIG. 5. Vital capacity (VC) and expiratory reserve volume (ERV) fell during the first 4 days of the 12-day exposure to 89.6% helium, 5.0% nitrogen, and 3.6% oxygen at 7.0 Ata. The cause of the change is not known. Brackets indicate the range of data.

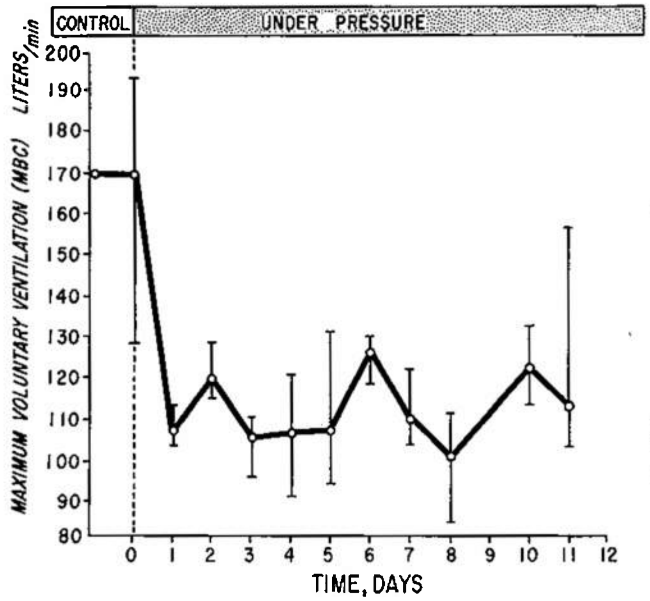

FIG. 6. Maximum breathing capacity before and during exposure to 7.0 Ata in 89.6% helium, 5.0% nitrogen, and 3.6% oxygen. The MBC decreased 38% on the first day of compression. There were no significant alterations thereafter. This decrease is the same as that which occurred during acute exposure to air under high pressure indicating that prolonged exposure to high pressure in helium has no progressive detrimental effect on maximum breathing capacity.

12 day compression. His enthusiasm and drive were major factors in the over-all morale of the group during this tedious and fatiguing experience. While a small amount of helium may have been present in alveolar gas as washout from body tissues during the period immediately following decompression, its concentration would have been too small to appreciably affect the total density of the exhaled gas. The high flow values at 50 and 85 % of the vital capacity in air in all three subjects may be related to previous diving experience. It is known that vital capacity increases in divers subjected to months of daily breath-hold diving to 100 ft (3).

A decrease in vital capacity and expiratory reserve volume was observed in all subjects during the first day of pressurization (Fig. 5). These changes persisted for 4 days. The apparatus was carefully checked for leaks but none were found. Maximum breathing capacity also decreased (Fig. 6).

DISCUSSION

This study demonstrates that under high ambient pressure in air the changes in flow observed from 1.0 to 4.0 Ata are the result of the increased density of the respiratory medium. This allows the following generalization to be made about the nature of maximum expiratory gas flow in normal man: the effect on flow of an increase in density of the respiratory medium is the same whether the change in density is produced by an increase in the number of molecules moving in the airway, i.e., due to an increased ambient pressure, or by an increase in the weight of the individual molecules. Theoretically

then, one should be able to simulate the change in expiratory flow at 20 Ata in air by doubling the molecular weight of the respiratory medium at sea level and pressurizing the subject and his breathing mixture to 10 Ata.

The decrease in maximum flow is not uniform throughout all lung volumes during expiration. As ambient pressure rises, peak flow is affected first. Above 4 Ata, little change in peak flow occurs while low lung volume flow diminishes. By contrast, low lung volume flow is little affected in the pressure range from 1.0 to 4.0 Ata; whereas, above 4.0 Ata, low lung volume flow decreases. In the pressure range used by most hyperbaric oxygen chambers, i.e., from 2.0 to 3.0 Ata, the greatest decrease in maximum flow occurs at a high lung volume above that used for normal tidal ventilation. Thus, as oxygen[4] and air have roughly the same density at sea level, normal tidal ventilation should not be greatly affected by the density change under pressure.

The data of Schilder, Roberts, and Fry (19) obtained from a normal subject breathing high molecular weight gases differ slightly from the data obtained under pressure in the present study (Fig. 1). For example, there is a small difference in flow rate at 50 % of the vital capacity. In Schilder's study the subjects breathed the high molecular weight mixtures for brief periods, while the subjects in the present study were maintained at each pressure for several minutes. Moreover, measurements of flow in the present study were made during decompression from 7.0 Ata. The cooling and condensation which occurs during decompression essentially saturates the ambient air with moisture. The changes due to this damp atmosphere were thus superimposed on the change from pressure alone. Also, the physical characteristics of the subjects and recording equipment differed. Taking these differences into account, the change in flow rate observed using the two methods is remarkably similar.

During the 12-day exposure to 7.0 Ata in 90% helium, the subjects remained alert and symptom free. None of the manifestations of oxygen toxicity were evident even though the ambient oxygen partial pressure was above normal. After 10 days the changes in expiratory flow were the same as during an acute exposure. Thus, there is no evidence for any progressive decrement in gas flow during prolonged high pressure exposure to helium.

The effect on gas flow of the increased viscosity of helium is minor at 1.0 Ata. Viscosity (unlike density) does not increase with increasing pressure in the ranges used in deep sea diving. It is unlikely, therefore, that the viscosity of helium will prove a major limiting factor in its use under pressure.

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[4] Oxygen density = 1.429 g/liter, air = 1.293 g/liter at sea level.